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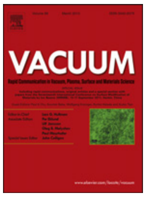

Effects of nanocrystalline silver incorporation on sliding tribological properties of Ag-containing diamond-like carbon films in multi-ion beam assisted deposition

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ABSTRACT

Ag-DLC different films with six Ag contents on AISI 440 steel substrate were deposited with a multi-ion beam assisted deposition, and attempt to correlate the incorporation of silver with the sliding tribological behavior was performed. Results show that: (i) increasing Ag content leading to an upward tendency of Ag of nanocrystallite size; (ii) superior tribological behaviors for the films with Ag content ranging between 4.3 and 10.6 at%; and (iii) the best tribological behaviors for the film of 8.3 at% Ag and 12.9 grain size. It also confirms that the evolution of the tribological properties is closely related to the level of the interaction of incorporated silver in forming sp^3 hybridization in the DLC films. These phenomena imply that the energetic particles may induce a balance between the recombination of particles and the change of internal stress in the DLC films.

1. Introduction

Diamond-like carbon (DLC) films show combined properties of high hardness and smooth surface, and thus have drawn attention for applications as wear-protective candidate in green precision manufacturing in the last decades [1]. While the major interest for DLC film of higher hardness is jeopardized due to their insufficient toughness to resist cross-sectional crack propagation [2], the industrial market urges to synthesize DLC film with both high hardness and good toughness. Recent interest has thus been focused on forming sp^3-C, introducing metal phase in amorphous carbon matrix, Me-DLC film (Metal-containing DLC), so as to alleviate the high compressive stress. Available studies in introducing the carbide forming elements like Ti [3], W [4] and Cr [5] into DLC films have shown an improvement of better hardness. However, the problem of high inherent stress and brittleness still remains. None carbide forming metals (like Cu, Ag, Au) containing DLC films have brought a hope for new tribological films that may replace their carbide forming counterparts [6]. As a soft and ductile element, Ag, embeded into the amorphous carbon matrix, may improve material tribological properties by lowering brittleness rates so as to increase toughness. Our previous works [6,7] on hard Ag-DLC films fabricated in mid-frequency dual-magnetron sputtering suggested that the differences among the mechanical and tribological properties could be partly explained by the variation of Ag contents and grain sizes. Unfortunately, the energy and flux of energetic particles in the deposition system are difficult to be controlled accurately and hence it is impossible to reveal fully the influence of silver incorporation into DLC matrix.

In this work, we aim at finding an appropriate range of Ag content and nanostructure size in Ag-DLC films deposited in IBAD (ion beam assisted deposition) system for optimizing their tribological properties and hence lengthening their service life. The IBAD system has the merit to control energetic particles precisely by adjusting independently the particle flux, energy, and incidence angle. We then went on to examine the possibility of adjusting both the tribological life and ductility by a proper incorporation of nanocrystalline Ag into the DLC matrix.

2. Experimental details

2.1. Coating procedures

Sheets of AISI 440 steel were machined to uniform dimensions and used as substrates. The steel sheets were ultrasonically cleaned in an acetone bath for 20 min and blow-dried with nitrogen. A multi-ion beam assisted deposition system shown schematically in Fig. 1 was employed to deposit the Ag-DLC films. The deposition system consisted of four Kaufman ion sources to give different ion energies. They were: (i) a high-energy source for ion implantation

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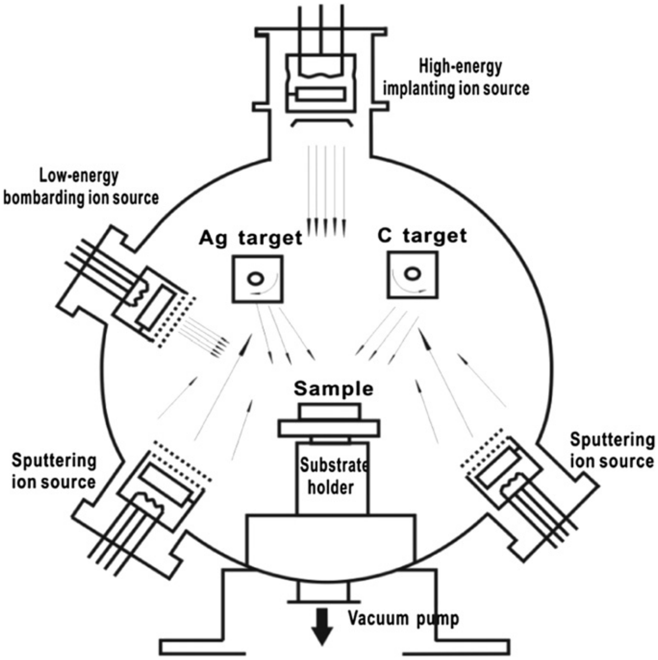

Fig. 1. Schematic diagram of multi-ion beam deposition system.

before sputtering, (ii) two middle-energy sources for sputtering the targets of silver (Ag) and graphite (C), respectively, and (iii) a low-energy source for ion bombardment during deposition. Its base vacuum was 2×10^{-4} Pa and deposition pressure was set to 1.5×10^{-2} Pa. The substrate was implanted with Ar^+ beam of 15 kV for 10 min to coat a favorable interfacial transition layer, followed by depositing a 0.2 μm thick Ag interlayer on the substrate by singular sputtering of Ag target at 1000 eV/30 mA. A 0.8 μm thick a:C-$Ag_{x\%}$ layer was subsequently synthesized by co-sputtering Ag and C targets together with a simultaneous Ar^+ beam bombardment of 80 eV. The co-sputtering was performed by varying the Ag sputtering current in range of 0–130 mA, and by fixing (i) its energy at 800 eV and (ii) the current and energy of the C sputtering at 50 mA and 1100 eV, respectively. The six different Ag-DLC films are fabricated.

2.2. Surface analysis methods

Ag content in the fabricated films was determined using energy dispersive spectrometer (EDS). Structure characteristics were analyzed using Raman spectroscopy. Ag grain size was determined by substituting values of half fullwidth of the peaks and their Bragg angles from X-ray diffractometer (XRD) measurements into the Scherrer formula. Tribological behavior in ambient atmospheric condition was evaluated using a ball-on-disk tester under 5 N normal load and at a linear sliding speed of 0.85 ms^{-1} for a distance of 1000 m. An optical microscope with digital camera attached in-situ sliding path for observing the wear traces on balls and discs. A surface profiler was used to observe the cross-sectional area of the worn section.

3. Results and discussion

3.1. Tribological properties of Ag-DLC films

Fig. 2 shows the change of steady-state coefficient of friction (COF) μ and wear rate of the Ag-DLC films, respectively. The steady-state μ value of the films varies between 0.090 and 0.207. The COF of 0.207 for a: C–$Ag_{0\%}$ film is close to that of pure sputtered DLC films available in the literature [8]. When the amount of Ag is increased, the value of μ initially at a maximum value of 0.207 for a:C–$Ag_{0\%}$ decreases to a value of 0.114 for a:C–$Ag_{4.3\%}$. It then reaches a minimum value of 0.090 when the Ag content is increased to 8.3 at% for a:C–$Ag_{8.3\%}$, followed by a gradual rise to 0.097 for a:C–$Ag_{10.6\%}$. As the Ag content is increased to 14.2 at%, the value of μ reaches 0.120, then it rises quickly to 0.164 for the a:C–$Ag_{25.8\%}$. The values of wear rate shown in Fig. 2 are in the range of 3.8–7.9 × 10^{-9} mm^3/Nm by having an accuracy within ±5%. It exhibits a similar trend as that of μ for the range of Ag incorporation used.

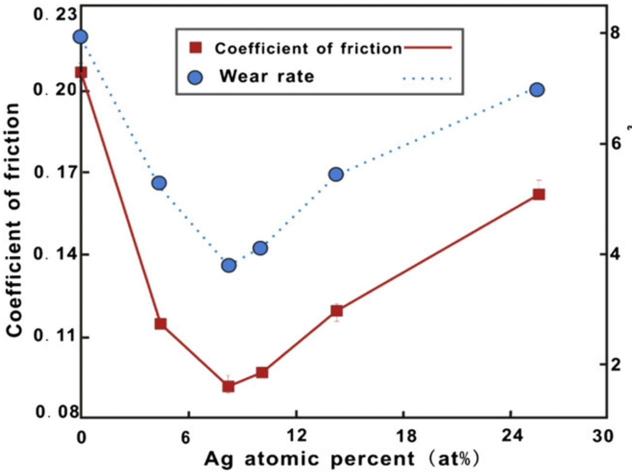

Fig. 2. Effect of Ag content on frictional coefficient and wear rate of Ag-DLC films.

3.2. Wear trace analysis of ball and disc in ball-on-disc testing

In Fig. 3, we show the typical disc morphologies with the insertion of their corresponding ball images at their respective top left corner. It shows that the DLC film with Ag-free DLC film has been peeled off from the surface in the process of sliding wear test (Fig. 3a). The chromatic wear track in Fig. 3a reveals that the possible formation of oxide is mainly due to the occurrence of temperature spikes at the asperity contacts between the counter-mating steel ball and the film. Fig. 3b and its inset is used to show that the wear of specimen a:C–$Ag_{4.3\%}$ is milder than the counterpart of pure DLC film. But its wear is more serious than that of the a:C–$Ag_{8.3\%}$ film (Fig. 3c). Specimen of a:C–$Ag_{8.3\%}$ has exhibited the lowest COF and excellent wear resistance since the wear track and the disc are very smooth after the test although there is single of wear debris just accumulating on both track and ball (Fig. 3c).

The wear for the sample a:C–$Ag_{10.6\%}$ (Fig. 3d) is a little more severe than that of the sample a:C–$Ag_{8.3\%}$ as appearance of wear debris at two sides of the wear track on the disc can be observed. Sign of an obvious transfer layer can be identified in Fig. 3e, seemingly conforming with the wear situation of sample a:C–$Ag_{14.2\%}$ with rapidly rising corresponding COF in Fig. 2. EDS analysis on the worn surface of both the ball and the transfer layer surface (Fig. 3e) suggested the presence of elements Fe and Cr, mainly from AISI440 substrate while Ag comes from the film. This, therefore, implies that the transfer layer is a result of the interaction of Ag-DLC film with steel substrate. In the slide wear track of a:C–$Ag_{25.8\%}$ film (Fig. 3f), a large amount of accumulated materials and some breakages were observed at a fringe of the track. This characteristic may be due to its relatively low hardness as a result of